Aerospace Systems Afloat: Present and Future

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Introduction

Aerospace systems have gone to sea in various forms for most of the last century as flying boats, aircraft carriers, and ballistic missile submarines. Two very interesting new concepts have peaked the interest of the aerospace community during the last few years: SeaLaunch$_{SM}$ [1] and SeaBase^{TM} [2]. Both are based on semi-submersible marine engineering technology, with the former presently operational while the latter exists only as a conceptual design. Others believe that the future will yield a very large float structure such as the MegaFoat [3] concept. MegaFloat represents a significant extension of the SeaBase concept by being a full size floating airport, with at least one main runway and a conventional taxiway. Much like the SeaLaunch technology breakthrough, the Megafloat will extent the technology envelope only if certain critical operation issues can be addressed. One issue specific to aircraft operations is precision approach and landing technology.

Present

The present marriage of aerospace and marine technologies is represented by the SeaLaunch system. The system brings together perfected semi-submersible marine platform technology with launch vehicles developed for ground based applications. The primary enabling technological advancement in is the relative stability of the launch platform. Perfected during the 1980's for the oil industry, the SeaLaunch platform's intrinsic 1 degree pitch and role stability is key to its precision launch capability.

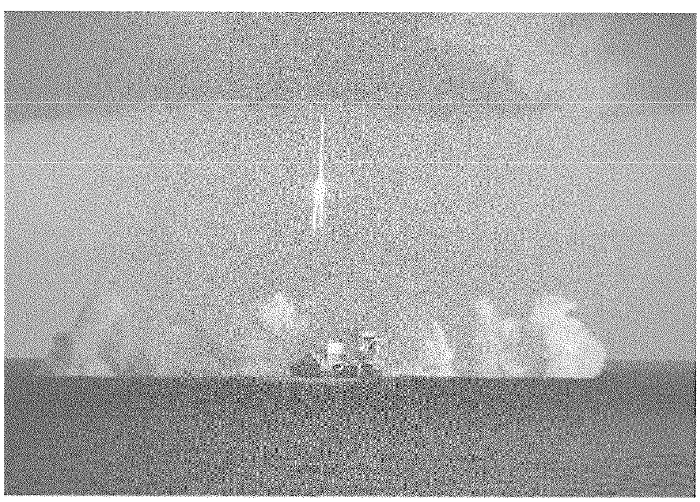


Figure 1 Satellite launch from Odyssey platform

SeaLaunch$_{SM}$

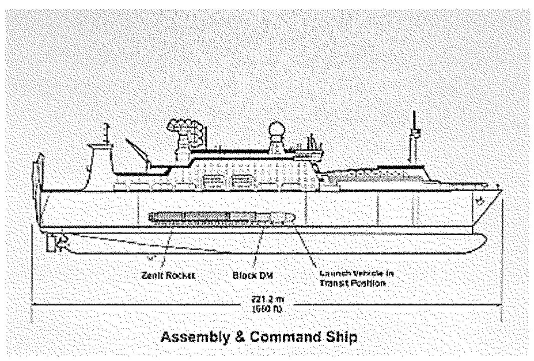
The SeaLaunch system is owned by the Sea Launch Limited Partnership. The partners are: Boeing Commercial Space Company (US), RSC Energia (Russia), KB Yuzhnoye/PO Yuzhmash (Ukraine), and Kvaerner Group (Norway). The system of the Assembly & Command Ship, the Launch Platform, and the Launch Vehicle.

A sea based operational concept provides a number of advantages over traditional launch systems using land sites. The spacecraft can be launched from the sea in any desired direction, largely unconstrained by terrain or overflight considerations. Geosynchronous satellites can be launched from equatorial or near equatorial sites, which should improve the payload-to-orbit efficiency by eliminating costly plane change maneuvers. The SeaLaunch concept also reduces the launch site infrastructure and support costs associated with the land based sites. The system can accommodate different types of spacecraft with minimum design changes. Other features include lower unit cost and shorter manufacturing flow time by avoiding competition for launch sites and vastly reducing the amount of time needed to prepare the launch pad before liftoff. Figure 1 shows a typical launch event from the SeaLaunch platform.

Assembly & Command Ship

The Assembly and Command Ship (Figure 2) is newly designed vessel that functions as an in-port floating rocket assembly factory, accommodations for customers and crew, and the mission control facility at sea. The ship was built at the Govan Shipyard in Glasgow, Scotland. In the fall of 1997, the it sailed to Russia, where special equipment was added for handling rocket components and command & controlling operations. The ship then sailed to Long Beach, Calif., on July 13, 1998, after a voyage through the Panama Canal.

The ship is 200 m (660 ft) long, approximately 32 m (106 ft) wide, with a displacement of more than 30,844 tonnes (34,000 tons) and has a cruising range of 18,000 nautical miles. The ship provides accommodations for up to 240 crew members, customers and VIPs—including medical facilities, dining room, recreation and entertainment facilities.



Assembly & Command Ship

Figure 2 Assembly & Command Ship showing integrated launch vehicle

Platform Launch

The Launch Platform, illustrated in Figure 3, is a former North Sea oil drilling platform, which was refurbished at the Rosenberg Shipyard in Stavanger, Norway. The platform, at 133 m (436 ft) long, and 78 m by 66.8 m (256 ft x 219 ft) of deck area, is one of the largest self-propelled semi-submersible vessels in the world. The propulsion system consists of a four thusters powered by eight direct current double armature motors rated at 3000 hp each. The platform has an empty transit draft displacement of 27,400 tonnes (30,100 tons), and a submerged operational draft displacement of 45904 tonnes (50,600 tons). When submerged, the ballasting system is able to achieve stability within approximately 1 degree. The ballast system uses tanks which are located in the pontoons and in the lower part of the columns, these are served by three ballast control pumps in each pontoon.

The Launch Platform provides living, dining, medial and recreation facilities for 68 crew and launch system personnel. It is equipped with a large, environmentally controlled hangar for storage of the Sea Launch rocket during transit, and with mobile transporter/erector equipment that is used to roll out and erect the rocket in launch position prior to fueling and launch. Special facilities onboard enable the storage of kerosene and liquid oxygen rocket fuels sufficient for each mission.

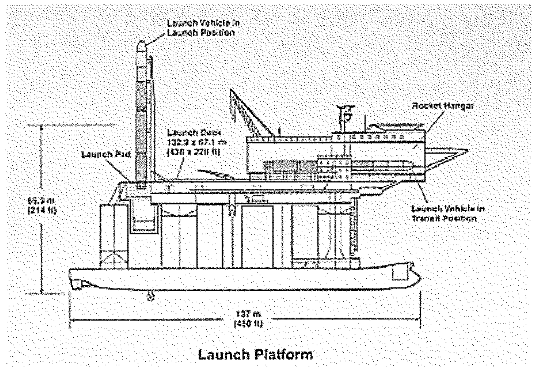


Figure 3 General configuration of launch platform for both transit and launch conditions

Launch Vehicle

The Zenit-3SL is a liquid propellant launch vehicle system capable of transporting 5000 kg spacecraft to a variety of orbits. Figure 4 illustrates the Zenit-3SL principal components. The basic two-stage Zenit is an existing design that was developed by KB Yuzhnoye to provide the capability to quickly reconstitute Russian satellite constellations. The primary structure is aluminum with integrated machined stiffeners. The engines that power the Zenit burn liquid oxygen and kerosene. Stage 1/2 separation is accomplished through the use of forward-firing, solid propellant thrusters located in the aft end of the first stage.

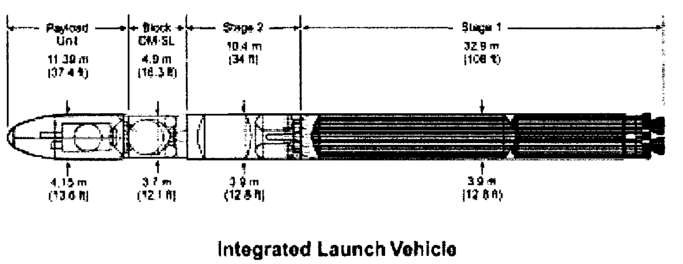


Figure 4 Integrated launch vehicle

Future

The future marriage of aerospace and marine engineering technology will be expressed in the form of floating airports. Practical needs versus cost will decide whether a deep ocean semi-submersible system or a full sized harbor based system will be realized first or at all. Ultimately the commercial world will set the pace for development and operation. Fundamental to both systems is the need to be able to operate aircraft in low visibility conditions. Takeoff, Approach and Landing operations have traditionally used the Instrument Landing System (ILS) as the primary source of guidance. The Microwave Landing System (MLS) was developed as a replacement for ILS but to date, has not been introduced in any significant numbers. Work is underway to develop landing aids based on the Global Navigation Satellite System (GNSS) as a GNSS Landing System (GLS). The GLS is a safety-critical system consisting of the hardware and software that augments the GPS Standard Positioning Service to provide for precision approach and landing capability The positioning service provided by GPS is insufficient to meet the integrity, continuity, accuracy, and availability demands of precision approach and landing navigation. The GLS augments the basic GPS position data in order to meet these requirements. These augmentations are based on differential GPS concepts [4]. Airfield stability although critical for the successful landing of aircraft is not a problem for land based airports. Each of these floating technologies suffers from accumulative motion errors. For a floating airport relative motion of the airport must also be included in the system error budget. The landing operation will be most difficult during weather conditions which include a wet runway, wind gusts, cross winds, and severely limited visibility. Figure 5 illustrates the typical landing area during good visibility conditions.

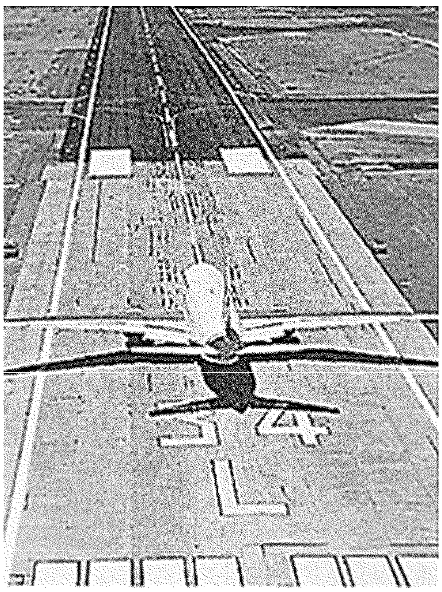


Figure 5 Clear weather landing touch down environment

Floating Airports

Floating airfields have been a topic of speculation and research for many years. Floating airport are man made islands, which can be located generally anywhere in the ocean. The earliest concepts for floating airport were motivated by the need to have way stations to support refueling of aircraft, which were unable to fly continuously across the major oceans. With the advent of extended range commercial air this need has disappeared. Floating airfields have continued to be of interest because they promise to liberate precious land for uses other than airports in densely populated areas of the world or countries with very little usable land.

General Configurations

Recent research has concentrated on two general configurations: mobile floating and fixed floating airport concepts. An example of a mobile floating concept is shown in Figure 6. The marine structure is based on semi-submersible technology derived from the oil industry. A modular design is shown which can be assembled to achieve a runway long enough to support large aircraft operations, yet capable of being relocate to different ocean regions This mobile floating airport concept is best suited for deep open ocean and is in general incompatible with shallower littoral areas. The feasibility of modular floating airports has been extensively studied by the US Office of Naval Research [5].

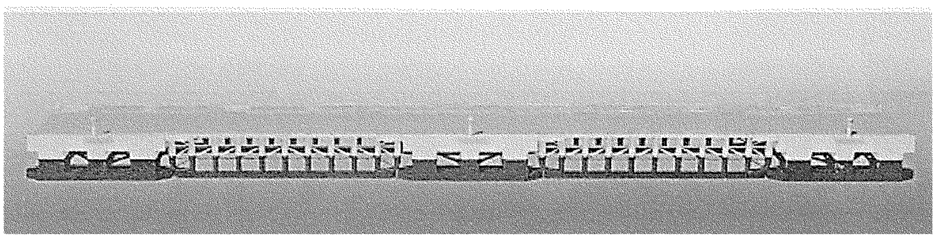


Figure 6 Mobile floating airport concept

Figure 7 illustrates an example of a fixed floating airport concept. This design would include runways, taxiways, and other infrastructure commonly found at a full size land based facility. Unlike the mobile platform, the fixed platform must be positioned in a protected harbor environment close to shore.

Figure 7 Very large fixed floating airport concept

Relative motion of these platforms may present problems for all types of precision landing systems. By their nature these structures will exhibit simple six degree of freedom motion as well as intra-platform structural bending modes of oscillation driven by the action of winds, waves, and tides. These motions will translate into errors in the glide slope an localizer position data displayed to the pilot on board the landing aircraft. Figure 8 shows a typical cockpit display system and pilot's view forward for a Boeing 777 aircraft. The glide slope and localizer information is presented on the flight guidance display in such a way to assist the pilot toward the correct touchdown point on the runway. Maintaining the

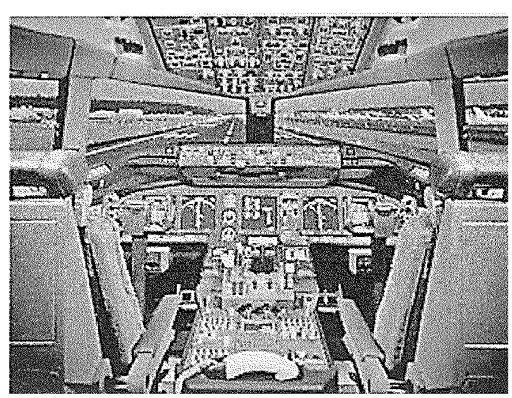


Figure 8 Electronic Flight Instrumentation System

correct touchdown point is important to insure that the aircraft ground roll is limited to the available runway length.

General Process for Insertion of New Airport Technology

New technology concepts for floating airports will need to be initially tested in a generic demonstration in a fully operational simulation facility. The demonstration should include weather, crew complement, airborne systems and any other relevant parameters necessary to show concept validity. Validity is expressed in terms of performance, system reliability, repeatability, and typical pilot response to failures as well as to demonstrate that an equivalent level of safety is provided.

Final Proof-of-Concept may be established by a combination of analysis, simulation, and flight demonstrations in a true operational environment. The overall Proof-of-Concept process is typically a combined effort among the FAA airworthiness organizations, operational organizations, and the applicants, with input from any associated or interested organizations. A typical Proof-of-Concept program consists of the following elements illustrated in Figure 9. In general the process involves four parties: aircraft manufacturer, aircraft operator, airport facility, and national/international regulatory agencies. If a new technology, such as a modified differential GPS system, were to be introduced then the process flow would be used to generate an amended Advisory Circular. A modified differential GPS system might be one that combines relative motion data for a large floating airport platform together with the differential GPS data.

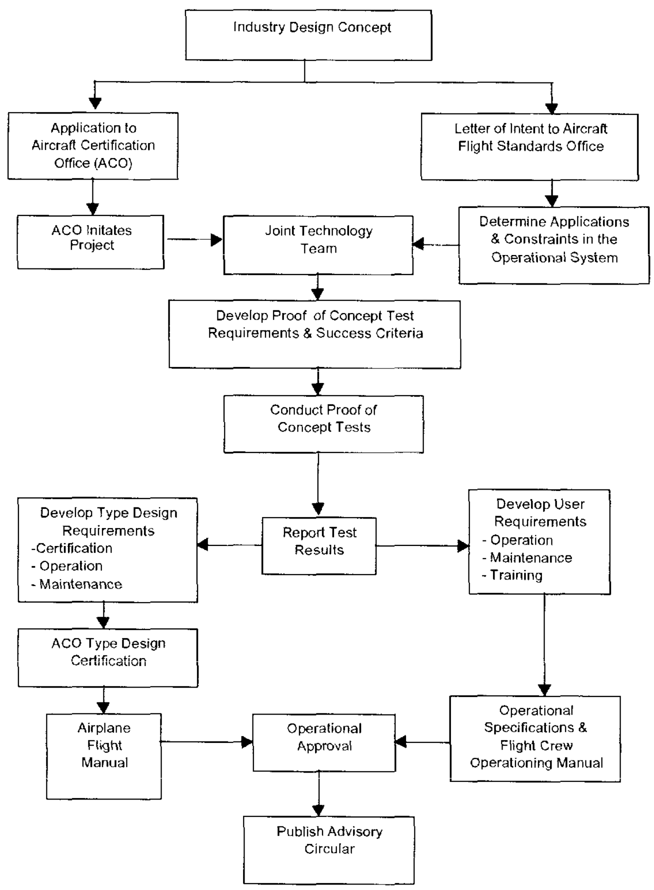


Figure 9 Process flow diagram of the technology insertion process

Operational Evaluation Process

The existing Advisory Circular for limited visibility ILS landings [6] considers the situation of "special terrain". Although the reference to terrain is for variable approach conditions relative to a land based situation, we might consider using a similar evaluation procedure for a dynamic airport such as MegaFloat. Special terrain for our example here may mean that the airport moves not only in six-degrees of freedom as a rigid body, but also via intra-platform flexure modes. The following information describes a recommended operational evaluation process, procedures, and criteria which might be used to characterize a floating airport. The process could be used during the airport research and development phase as well as later for operational certification.

Evaluation

The following process lists those steps that should be considered to assess and verify normal flight guidance system performance from an operational perspective, and identify miscellaneous factors for safe low visibility aircraft operation.

Procedure.

Perform at least 4 to 6 successful evaluation landings in typical atmospheric conditions regarding wind and turbulence, using the applicable operational aircraft configuration, with a representative aircraft from the fleet. If the flight guidance system may be susceptible to an uncertain performance characteristic (e.g., long flare in a tailwind condition, pitch/throttle coupling oscillation during flare) the evaluation should take place when the system may be put to an appropriate test of the applicable crosswind, tailwind, headwind, wind gradient, or other critical condition applicable, consistent with the operator's proposed conditions or limits. Confirm the initial assessment of 4 to 6 data recorded evaluation landings, with subsequent successful initial operational landings (typically the first 25 or more) as reported by the operator.

Evaluator(s).

A person qualified to assess flight guidance system function and performance should conduct these evaluations as the FAA observer. FAA may designate other suitably qualified representatives to assess flight guidance system function and performance as necessary.

FGS Performance and Data Recording.

Generally, some form of quantitative data should be recorded and reviewed as verification of performance. Methods used in the past include, but are not limited to either Method A, or Method B, or Method C below or any combination:

Method A

Data Recording and Observation. - Record pertinent flight guidance system performance data recorder, or equivalent, which has ability to record the parameters shown below.

barometric altitude	glide slope error	pitch attitude
radio altitude	vertical speed	throttle position
radio altitude rate	elevator command	airspeed

Manual observations may be made for touchdown point (lateral, longitudinal), wind profile from 1000 ft. to surface.

Method B

Review of Manufacturer's Data. - A review of the manufacturer's data from flight guidance system development flight testing at the same special terrain runway, or equivalent, may be used to confirm data items shown below in Data Review and Analysis.

Method C

Photo Recording - Photo recording of pertinent instruments or instruments and outside view, with a video camera or equivalent, allowing post flight replay and review of indications noted in Method A above.

Data review and Analysis

The final approach, flare, and touchdown profile should be reviewed to ensure suitability of at least each of the following:

a) Suitability of the resulting flight path

b) Acceptability of any flight path displacement from the nominal path (e.g., Glide slope deviation, deviation from nominal flare profile),

c) Proper mode switching

d) Suitable touchdown point,

e) Suitable sink rate at touch down,

f) Proper flare initiation altitude

g) Suitable flare "quality" (e.g., no evidence of early or late flare, no overflare or underflare, no undue "pitchdown down" tendency at flare initiation or during flare, no flare oscillation, no abrupt flare, no inappropriate pitch response during flare, no unacceptable floating tendency, or other unacceptable characteristic that a pilot could interpret as failure or inappropriate response of the flight guidance system and disconnect, disregard, or contradict the FGS),

h) No unusual flight control displacements (e.g., elevator control input spikes, or oscillations),

i) Appropriate throttle retard (e.g., no early or late throttle retard, no failure to retard, no undue reversal of the retard, no undue pitch/throttle coupling),

j) Appropriate speed decay in flare (e.g., no unusually low speed risking high pitch attitude and tail strike, no excessive float, appropriate speed decay even if well above V_{ref} at flare initiation due to planned wind or gust compensation),

k) Proper mode initiation or mode transition relating to altitude or radio altitude inputs, such as crosswind alignment initiation, if applicable (e.g., Appropriate radio altitude (RA) trigger of crosswind alignment, to be sure that an appropriate mode transition occurs, even though underlying approach terrain may be irregular).

Miscellaneous Issues.

a). Determine acceptability of any variable radio altitude indications. Regarding Alert Height (AH) or Decision Height (DH) identification, determine the acceptability of any variable radio altitude indications or displays. Assure that display indications are sufficiently stable and continuous to readily identify or define AH or DH.

b) Address any anomalies occurring during the assessment (e.g., autopilot trip, firm landing, flare oscillation). Additional testing may be needed to clearly identify and resolve any particular problem identified.

c) Determine if special training, or other operational constraints are needed to accommodate peculiar approach or flare characteristics (e.g., require visual reference at flare initiation, apply a 50 ft. DH).

d) Authorization for use should occur only after repeated successful landings have been demonstrated and any anomalies experienced have been resolved.

Conclusions

One of the best demonstrations of present day commercial aerospace systems afloat is the SeaLaunch satellite launch system. The future will give us grander and more significant aerospace systems such as Mega-Float. The Mega-Float floating airport concept will however need further research in critical areas such as precision landing systems technologies. An evaluation methodology has been suggested for floating airport concepts which could be applied to both R&D as well as later certification. Research efforts should focus now on landing system performance analysis and piloted simulations in order to better understand the sources of errors due to platform motion. These research efforts will help develop technical solutions which later can be included into practical airport designs.

References

1) All information regarding SeaLaunch was provided by SeaLaunch Company, LDC and has been cleared for public release by the Department of Defense, Directorate for Freedom of Information and Security Review, as stated in letter 98-S-4071, dated 17 November 1998.
2) SeaBase is a conceptual design developed by Moss Maritime, Lysaker, Norway.
3) MegaFloat airport is a conceptual design under development by the Technical Research Association of MegaFloat, Tokyo, Japan.
4) See for example Trimble Navigation Limited at (http://www.trimble.com/gps/diffgps/gpsfram1.htm)
5) See (http://mob.nfesc.navy.mil/)
6) US Department of Transportation, Federal Aviation Administration, Advisory Circular AC 120-28D.